FUZZY COLOURED PETRI NETS IN MODELLING FLEXIBLE MANUFACTURING SYSTEMS

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ABSTRACT

Recently, Coloured Petri Nets (CPNs) have been widely used for modelling asynchronous discrete events exhibited in dynamic systems, while Fuzzy Petri Nets (FPNs) used for systems that involve approximate reasoning and uncertainty knowledge inference. In this paper, we propose a net-based structure, the so-called Fuzzy Coloured Petri Nets (FCPNs) to model both the dynamic behaviour and inexact production inference of Flexible Manufacturing Systems (FMSs). Our approach is based on the integration of the concepts of CPNs and FPNs. It was applied to a typical FMS, i.e. a printed circuit board production system demonstrating the model's capability in simulating the system behaviour and fuzzy control rule's inference.

INTRODUCTION

FMS and Petri Nets

A flexible manufacturing system (FMS) is an integrated, computer-controlled configuration of some automated material handling devices and numerically controlled machines that can simultaneously process medium-sized volumes of a variety of part types. Such systems combine the advantages of very flexible but inefficient manual job shops with those highly productive but rigid transfer lines. Therefore, FMS is necessary to enable a manufacturer to compete efficiently in today's market. Nowadays, there are huge number of researches in progress in this area. However, they all share a common goal: to search for solutions to achieve higher speeds and more flexibility and thus increase manufacturing productivity. There are various modelling techniques for FMS, the most common one of these is based on mathematical programming. However, it cannot be satisfactory used or even impossible to apply for very complex systems. Another common approach is based on simulation. Petri nets based simulator is one of the most popular simulation languages used for analyzing complicated FMS systems. It is mostly used to aid the study of optimal operational setting problems by modelling concurrent FMS assembly systems and evaluating the production rates of various possible settings. Usually, there are some production strategies associated with these FMS, many of such strategies are expressed in the forms of fuzzy production rules, e.g. If the tool speed is high and the feed rate is small then the surface finish is high. In order to have an appropriate modelling language for FMS of the given complexity, we provide an extension of Petri nets to efficiently describe the concurrency, synchronization, and mutual exclusion of flexible manufacturing systems with fuzzy characterized behaviours.

Extensions of Petri Nets

We have seen the growing interest and importance in utilizing the Petri Nets (PNs) to model, simulate and analyze asynchronous, discrete event dynamic systems in the last two decades. It has been widely used in various application domains such as flexible manufacturing systems [4][9][11], expert system verification [7], communication protocol for digital telephone networks, VLSI chips, complex radar surveillance system, control of electronic transfer of money.

Some extensions of Petri Nets, such as Coloured Petri Nets (CPNs) [5][6] and High-Level Petri Nets (HLPNs), have been developed since ordinary Petri Nets are not always sufficient to represent and analyze complex system behaviour. The reasons for its success are: a graphical representation of the problem, well-defined semantics, ability to describe a large variety of different systems, few but powerful primitives, explicit description of both states and actions, concurrent semantic, hierarchical description, integration and synchronization of control and data manipulation, stability towards minor system changes, interactive simulation, formal analysis methods and supporting computer tools. Recently, there is a software system, Celeritas [1], using a Coloured Petri Nets approach to simulate and control Flexible Manufacturing Systems. In [10], authors have used CPNs to model hybrid rule/frame-based expert system.

However, classical Petri Nets have a lot of limitations requiring the provision of exact and precise description of the system. It may not be able to model incomplete, uncertain, and approximate information or states. As the popularity of fuzzy reasoning grows in certain kinds of manufacturing processes, it is necessary to extend Petri Nets to incorporate fuzzy logic in such processes. Therefore, Fuzzy Petri Nets (FPNs), a model which is able to represent the fuzzy production rules of a rule based system, is the ideal tool to aid such type of manufacturing system development [4][9]. However, until recently, there is no standardized definition of Fuzzy Petri Nets, therefore, in the present paper, we based on Chen's Fuzzy Petri Nets [2] concepts for production rules modelling and Jensen's Coloured Petri Nets [5][6] concepts for complex data structure modelling to formulate our extended model, Fuzzy Coloured Petri Nets (FCPNs).

It is noted that Fuzzy Petri Nets has been used in task sequencing in robotics system [3], knowledge acquisition and representation [2], approximate reasoning, medical diagnosis. A summary of the applications of Fuzzy Petri Net can be obtained in [8].

The application problem we consider here is: if there is a complex system, such as, Flexible Manufacturing Systems, with the following properties: concurrency, complex data structure and fuzzy rule-based production strategies that we need to model, it would be desirable to have a modelling tool which supports the abilities of both Fuzzy Petri Nets and Coloured Petri Nets.

In next section, the definition and the firing rules of FCPNs are described. In Case Study section, a flexible automatic printed circuit board component insertion assembly system is described. Basically, the system can be divided into two subsystems that should be integrated together. One of the subsystems is the robot arms operation sequencing system that can be efficiently modelled by CPNs. Another subsystem is the fuzzy robotics wrist control system. It cannot be modelled by CPNs itself without the use of FPN model. Using FCPNs, the two subsystems can be nicely integrated into one system that the modelling, simulation, analysis can be performed effectively.

FUZZY COLOURED PETRI NETS

Definition

Chen's Fuzzy Petri Net [2] and Jensen's Coloured Petri Nets [5][6] are the foundation of our proposed Fuzzy Coloured Petri Net (FCPN). A generalized non-hierarchical FCPN can be defined as an 12-tuple: **FCPN** = (Σ, P, T, D, A, N, C, G, E, β, f, I), where

$\Sigma = \{ \sigma_1, \sigma_2, ..., \sigma_l \}$, a finite set of non-empty types, called *colour sets*, $l \geq 0$,

$P = \{ P_C, P_F \}$ a finite set of *places*,

  $P_C = \{ pc_1, pc_2, ..., pc_m \}$, a finite set of places that model the dynamic control behaviour of system, called *control places*, $m \geq 0$,

  $P_F = \{ pf_1, pf_2, ..., pf_n \}$, a finite set of places that model the fuzzy production rules, called *fuzzy places*, $n \geq 0$, $P_C \cap P_F = \varnothing$,

$T = \{ T_C, T_F \}$, a finite set of *transitions*,

  $T_C = \{ tc_1, tc_2, ..., tc_i \}$, a finite set of transitions that are connected to and from *control places*, called *control transition*, $i \geq 0$,

  $T_F = \{ tf_1, tf_2, ..., tf_j \}$, a finite set of transitions that are connected to or from fuzzy places, called *fuzzy transition*, $j \geq 0$, $T_C \cap T_F = \varnothing$,

$D = \{ d_1, d_2, ..., d_h \}$, a finite set of *propositions*, $| P_F | = | D |$,

$A = \{ a_1, a_2, ..., a_k \}$, a finite set of *arcs*, $k \geq 0$, $P \cap T = P \cap A = T \cap A = \varnothing$,

$N : A \rightarrow P \times T \cup T \times P$, a *node function*, it maps each arc into a pair where the first element is the source node and the second is the destination node, the two nodes have to be of different kind,

  In: an *input function* that maps each node, x, to the set of nodes that are connected to x by an input arc of x;

  Out: an *output function* that maps each node, x, to the set of its nodes that are connected to x by an output arc of x,

$C : (P \cup T) \rightarrow \Sigma_{ss}$, a *colour function*, i.e. it maps each place and transition to a super-set of colour set,

$G : T \rightarrow$ expression, a *guard function*, $\forall t \in T$:[$Type(G(t))=Boolean \wedge Type(Var(G(t))) \subseteq \Sigma$], where $Type$(Vars) to denote the set of types $\{Type(\mathrm{v}) | \mathrm{v} \in \mathrm{Vars}\}$, Vars is a set of variables, $Var(G(t))$ denotes the variables used in $G(t)$,

$E : A \rightarrow$ *expression, an arc expression function,* $\forall a \in A$: $[Type(E(a))=C(p(a))MS \wedge Type(Var(E(a))) \subseteq \Sigma$] where $p(a)$ is the place of $N(a)$, MS stands for multi-set,

$\beta : P_F \rightarrow D$ is a bijective mapping from fuzzy places to proposition,

$f : T \rightarrow [0,1]$, an association function, assigns a certainty value to each colour used in each fuzzy transition,

I : an initialization double (δ , α),

$\delta : P \rightarrow$expression, an initialization function, $\forall p \in P$:[Type($\delta(p)$)=$C(p)_{MS}$],
α : an association function, assigns a certainty value in the range [0,1] to each token in the fuzzy places.

Firing Rules

For a Fuzzy Coloured Petri Nets, we need to pay special attention on the firing rules since there are integration between dynamics control part and fuzzy part of Petri nets.

Firing rules for a control transition are as follows:

- A transition fires if and only if the colour token in the input places of that transition are members of the colour set associated with the transition.
- The colour tokens are removed from the input places when a transition fires. A set of colour tokens will be created in the output places as defined by the expression of the output arc.
- Colours associated with tokens are allowed to change across transitions.

Firing rules for a fuzzy transition are as follows:

- All the firing rules are for a fuzzy transition.
- A transition fires if and only if all the certainty value (α) of the input tokens is larger than a threshold value where threshold value$\in$[0,1].
- Similar to the firing rules for the control transition, the firing process of the transition will remove the input tokens in their input places and will deposit tokens into each of its output places.
- The degree of truth of the output token will be the product of the certainty value of the input proposition and the strength of the belief in the rule (i.e. the certainty value of the fuzzy transition of the respective colour, *f*).

A Fuzzy Coloured Petri Nets Example

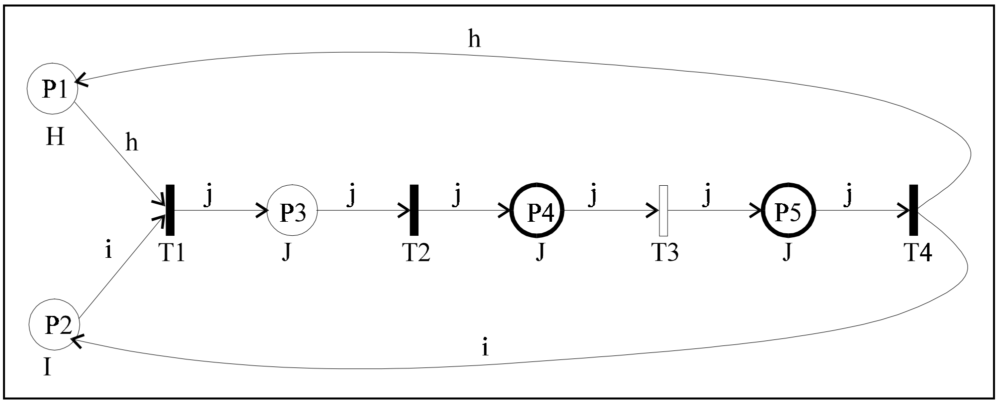

Figure 1. A Fuzzy Coloured Petri Net Example

To illustrate our definition of non-hierarchical *FCPNs*, the net in Figure 1 can be represented as the followings:

Σ = {H, I, J}. There are three colour sets used.
P = {P1, P2, P3, P4, P5}. Five places are used namely from P1 to P5.
P_C= {P1, P2, P3}. The first three places are for modelling control processes.
P_F= {P4, P5}. The last two places are for modelling fuzzy rule.
T = {T1, T2, T3, T4}. Four transitions used.
T_C = {T1, T2, T4}. These three transitions are for modelling control processes
T_F = {T3}. The transition T3 is for modelling fuzzy rule.
D = {d1, d2}. There are only one rule with two propositions. e.g. IF d1 THEN d2.
A = There are ten arcs used. e.g. arc1, arc2 ..arc 10 where {arc1:P1toT1, arc2:P2toT1, arc3:T1toP3, arc4:P3toT2, arc5:T2toP4, arc6:P4toT3, arc7:T3toP5, arc8:P5toT4, arc9:T4toP1, arc10:T4toP2}. ":" means from.
N(*a*) =A node function, which maps each arc into a pair where the first element is the source node and the second is the destination node. e.g. P1toT1, P2toT1, T1toP3, P3toT2, T2toP4, P4toT3, T3toP5, P5toT4, T4toP1, T4toP2.

$$C(p \cup t) = \begin{cases} \{H\} & \text{if} \quad p \in \{P1\}, \\ \{I\} & \text{if} \quad p \in \{P2\}, \\ \{J\} & \text{if} \quad p \in \{P3, P4, P5\}, \\ \{H, I\} & \text{if} \quad t \in \{T1\}, \\ \{j\} & \text{if} \quad t \in \{T2, T3, T4\} \end{cases}$$

The colour sets for each places and transitions are defined above.

$G(t)$ = True. All Guards are defined "True" i.e. no additional constraints in the firing of transitions.

$$E(a) = \begin{cases} h & \text{if} \quad a \in \{P1toT1, T4toP1\} \\ i & \text{if} \quad a \in \{P2toT1, T4toP2\} \\ j & \text{otherwise} \end{cases}$$

The arc expressions are defined as simply passing different types of token. (h, i and j)

$$\beta(pf) = \begin{cases} d1 & \text{if} \quad pf = P4, \\ d2 & \text{if} \quad pf = P5 \end{cases}$$

The rule's two prepositions are mapped to place for which P4 is the antecedent and P5 is the consequent.

$f{:}T \rightarrow [0,1]$.

We may assign 0.89, for example, as the certainty value to our fuzzy rule transition T3.

I : an initialization double (δ , α),

δ : $P \rightarrow$expression, an initialization function, $\forall p \in P$:[Type($\delta(p)$)=$C(p)_{MS}$]. This is the initial marking for the net.

α : an association function, assigns a certainty value in the range [0,1] to each token in the fuzzy places. This is the arc expression which assign a fuzzy value to the token after firing the rule. It is the product of the fuzzy value of the token initially carried with the rule's fuzzy value. (We may also apply some resolution operator to get the resultant value in case there exists more than a token of the same type.)

A CASE STUDY

System Description

One of the applications of Petri Net is to aid the production engineers to develop Flexible Manufacturing Systems (FMSs). Basically, the applications of Petri Net in FMSs could be classified into five different domains: modelling, qualitative and quantitative analysis, performance evaluation, scheduling and control implementations. In recent years, the development of automation in many production processes, especially in electronic production, are growing rapidly. However, in some processes, automated machines may not be able to achieve high degree of accurate performance which are comparable to that of skilled workers. Electronic components insertion on printed circuit boards is one typical process. According to [12], incorporating fuzzy rules in the automated insertion process will enable a smoother performance, and resulted a faster process towards a full insertion.

Multi-robot systems for printed circuit board (PCB) assembly have the following three features which are distinct from conventional systems for automated assembly of mechanical parts [15]:

- Numerous insertions are required for a moderately complex printed circuit board. The component count ranges from 100 to 200 per board. The activities for each board assembly are highly repetitive.

- There is no strict sequence which has to be followed. This means that the insertion order of components can be largely altered without affecting the outcome. While in many mechanical assembly tasks, assembly possibilities are often quite limited due to heavy precedence constraints.

- Each insertion is performed by one robot manipulator even in a multi-robot system. While in mechanical assembly, two or more robots may be involved in fulfilling a single operation.

The assembly station that we study on is AT&T FWS-200 flexible workstation. It will be briefly described here. The system consists of the following major components: frame structure, control cabinet, Robot Arms, AT&T PC386 computer, Drive Electronics Drawers, Control Panel, Vision System, Peripheral Equipment.

To improve the flexible workstation performance, we apply a robotic compliant wrist device which combines passive compliance and displacement sensor for robots to facilitate various complex manipulation tasks. When robots make contact with workpiece, the wrist provides the necessary flexibility to accommodate transitions to correct positioning error of robots and geometric tolerance of parts, and to avoid high impact forces normally generated in manufacturing operations. The sensing from the wrist device is used in the feedback loop for actively controlling contact forces and compensating for positioning errors during motion and contact. Since insertion operations when the wrist device is installed in robotic assembly, is inherently an ill-defined and complex process, fuzzy controllers might be more effective other than conventional controllers. The controller is comprised of four parts, fuzzification interface, knowledge base, decision making logic, and defuzzification interface. Membership functions and decision rules are deduced from operator experience and task requirement. Compared with the method of evaluating exact force zones, the fuzzy control approach presented a smoother performance, and yielded a fast process towards a full insertion.

Fuzzy Coloured Petri Net Modelling

In figure 2, the processes of flexible printed circuit board assembly workstation are modelled using our proposed Fuzzy Coloured Petri Nets methodology. There are eight places: Robot Available, Component Available, Feeder Area Available, Robot Picking, Robot Moving into PCB, Robot Inserting, Robot Moving out PCB, PCB Available.

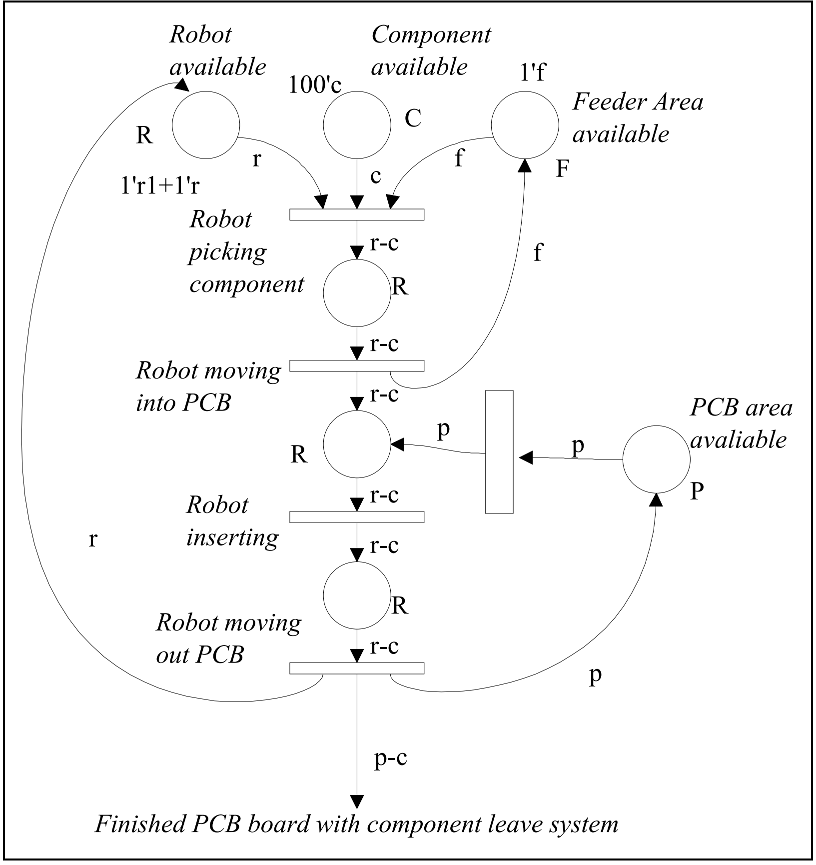

Figure 2. FCPN for the flexible PCB assembly workstation

At the initialization, there are two tokens, “r1” and “r2”, where “r1” represents the left robot arm while “r2” represents the right robot arm. This two tokens are inside the CPN place Robot Available, with colour R, where the number of tokens represents the number of components available. In this study, 100 components are chosen for illustration purpose. For simplicity reason, we assume that there is only one type of component with colour C. (In practical situation, the number of components is normally more than ten.) Besides, there is only one Feeder Area Available and one PCB Area Available, therefore, one feeder token is put inside the Feeder Area Available place and one PCB area token in the PCB Available place respectively. The mutual exclusive property of the feeder area and PCB area can be maintained during the simulation process. After the initialization, the first transition will consume one “r” token (either “r1” or “r2”), one “c” token and one “f” token, then a “r-c” token will be created in place Robot Picking, it means that the robot arm is holding the component. The robot arm will move to the PCB position and waiting for inserting. If the feeder area is available, then the robot arm will insert the component into the printed circuit board. During this insertion process, the robot arm must rotate in an angle such that the legs of the components are perpendicular to the PCB board. The rotation of the robot arm is controlled by a set of ten fuzzy production rules (see Figure 3). Typical rules may be:

Rule1 : IF X axis’s displacement is Small
AND
Z axis’s displacement is Small
THEN
X’s velocity is Zero

Rule2 : IF X axis’s displacement is Medium
AND
Z axis’s displacement is Small
THEN
X’s velocity is Small

In this part, we will utilize the special feature of the proposed Fuzzy Coloured Petri Nets to model the operation sequencing and the fuzzy control rules together. First, we have some readings about the angles of the component to be inserted with respect to the PCB board. (i.e. the x-axis, y-axis, z-axis displacements.) These three measurements are then fuzzified into eight fuzzy variables: x_ds, x_dm, y_ds, y_dm, z_ds, z_dm, z_db and z_dvb. (ds = displacement small, dm = displacement medium, db = displacement big and dvb = displacement very big). This eight fuzzy variables are used as inputs to ten fuzzy production rules. The rules' output will be defuzzified which gives the x_d and y_d values. If these two outputs are not zero, then they are used to feedback to the control of the robot arm. The new readings will be used to feed in the fuzzy control rules again until the x_d and y_d is zero, then the component will be inserted into the PCB and the finished PCB will leave the system.

The robot arm will move out from the PCB available area and the robot arm and the PCB area will be available again for the next component insertion. This process will keep on operating until all the components are used up.

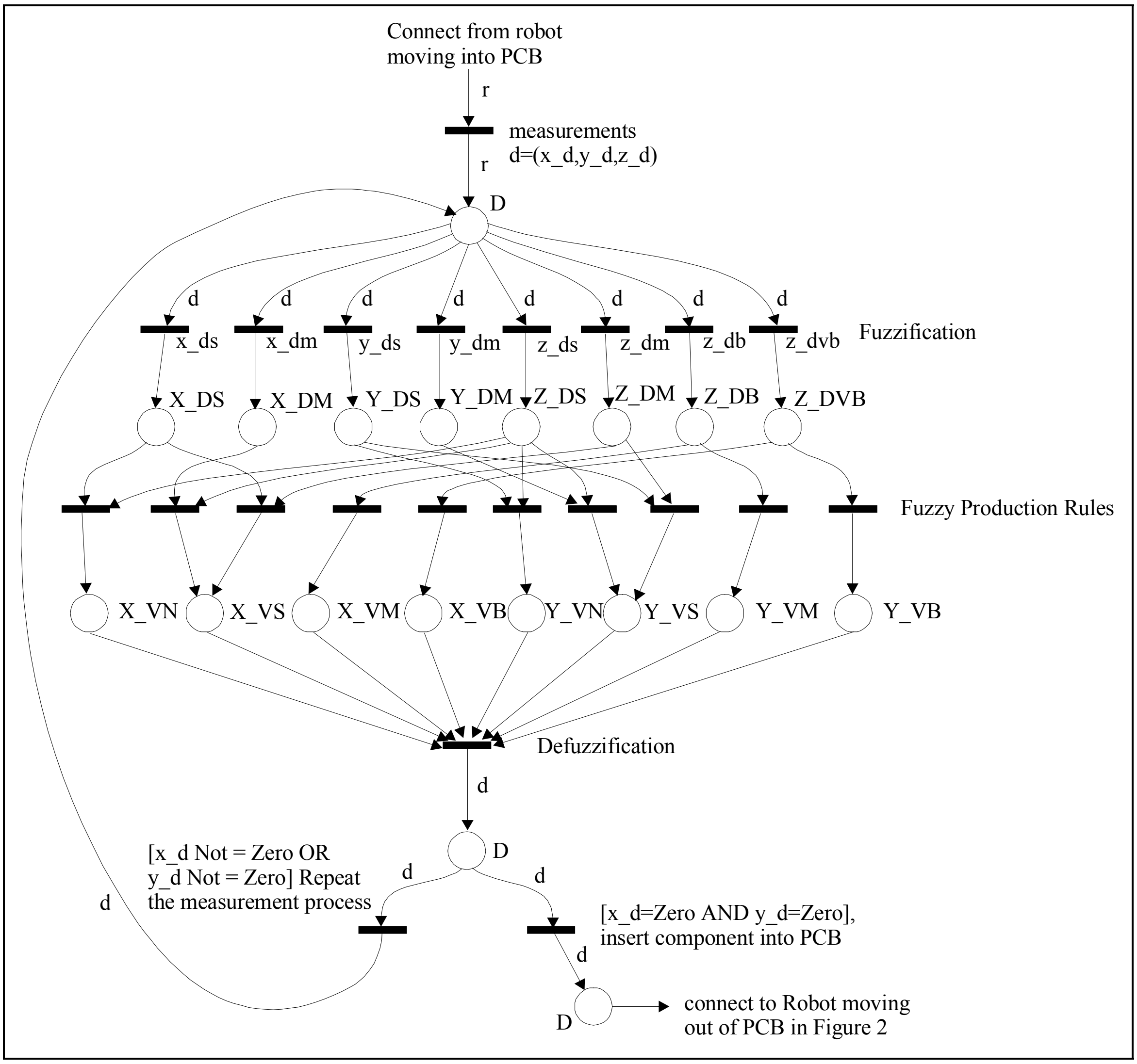

Figure 3. FPN for the fuzzy production rules of 'Robot inserting' place

CONCLUSION AND DISCUSSION

In this paper, a novice extension of Petri Nets, Fuzzy Coloured Petri Net (FCPN), is proposed. It combines the modelling power of both Fuzzy Petri Net and Coloured Petri Net while preserves the advantages of both nets. The power of FCPN is demonstrated in a case study of electronic components insertion process in Flexible PCB Manufacturing System. As shown in Figure 2 and Figure 3, we can conclude that Fuzzy Coloured Petri Net is able to contribute two significant advantages. The first advantage is that the dynamic and fuzzy control behaviour of the two robotic arms can be modelled by a single FCPN. Since CPN is unable to model fuzzy concept and FPN is unable to model the dynamic behaviour of the system, FCPN is a natural and powerful tool to model a system with fuzzy and dynamic processes. It also enables the whole system to be analyzed in one single net. The second advantage is that using FCPN will significantly reduce the graphical complexity. As we have shown in the case study, if only FPN is used alone, two identical FPNs are needed to model the fuzzy production rules associated with two identical robot arms. Therefore, FCPN not only provides a more concise graphical representation, it also demonstrates the power to use one kind of Petri Net to model the whole FMS which cannot be done the otherwise.

Some extensions of research are suggested here. First, further investigation in the applications of FCPN to FMS is needed in order to demonstrate how the technique can improve flexibility in design, system efficiency, cost effectiveness and the quality of products. Secondly, a user interface and animation should be implemented; by experimenting with different inputs and comparing the outputs in a duration period, a user can quickly determine how to improve the efficiency, reduce the cost, and pin down the bottleneck. Thirdly, an efficient Fuzzy Reasoning Algorithm for Fuzzy Coloured Petri Net should be further explored (e.g. Yeung's FRA for FPNs [13][14]). Furthermore, some system verification [10] should be investigated to strengthen the reliability of the FCPN model.

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